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# Self-contained Position Tracking of Human Movement Using Small Inertial/Magnetic Sensor Modules

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*Abstract*—**Numerous applications require a self-contained personal navigation system that works in indoor and outdoor environments, does not require any infrastructure support, and is not susceptible to jamming. Posture tracking with an array of inertial/magnetic sensors attached to individual human limb segments has been successfully demonstrated. The "sourceless" nature of this technique makes possible full body posture tracking in an area of unlimited size with no supporting infrastructure. Such sensor modules contain three orthogonally mounted angular rate sensors, three orthogonal linear accelerometers and three orthogonal magnetometers. This paper describes a method for using accelerometer data combined with orientation estimates from the same modules to calculate position during walking and running. The periodic nature of these motions includes short periods of zero foot velocity when the foot is in contact with the ground. This pattern allows for precise drift error correction. Relative position is calculated through double integration of drift corrected accelerometer data. Preliminary experimental results for various types of motion including walking, side stepping, and running.**

## I. Introduction

POSITION tracking of human movement commonly requires an unrestricted line of sight between one or more receivers and one or more transmitters. In inside-out systems a sensor attached to a person to be tracked, passively or actively receives information from multiple "sources" positioned around a tracking volume. In outside-in tracking systems, multiple sensors positioned around a tracking volume sense active or passive sources attached to the object to be tracked. The global positioning system (GPS) is a familiar example of a sourced inside-out tracking system. Optical tracking systems that use multiple cameras to view active or passive markers and calculate position through triangulation are an example of a sourced outside-in tracking system.

Inside-out or outside-in tracking systems require extensive set-up and calibration of the tracking volume. Line of site and noise restrictions limit range as well as where these systems can be used. In some cases jamming or intentional interference makes their use impractical. "Sourceless" systems are self-contained. Data that are produced by sensors attached to a person can be used to calculate position without reference to other devices or transmitters. In theory, a sourceless system with accuracy comparable to a sourced system is superior since it does not require extensive infrastructure positioned around or above a tracking environment of limited size, and is not susceptible to line of sight restrictions between a transmitter and source.

Sourceless orientation tracking using small inertial/magnetic sensor modules containing triads of orthogonally mounted accelerometers, angular rate sensors, and magnetometers has been successfully demonstrated. Several commercial posture tracking systems based on orientation tracking have resulted. The individual sensors used in inertial/magnetic sensor modules are low-cost Micro-Electro-Mechanical Systems (MEMS) sensors. Low cost MEMS accelerometers are susceptible to drift errors. Until recently, it was widely thought that position tracking using data from such accelerometers was not possible due to the quadratic growth of errors caused by sensor drift during double integration.

Most types of human movement including walking, side stepping, and running include repeated recognizable periods during which the velocity and acceleration of the foot are zero. These brief periods occur before entering the swing phase of the gait cycle each time the foot contacts the ground during the stance phase. Recognition of these periods allows determination of the drift error that occurred in between them. This allows precise corrections to be made to accelerometer data in either a forward or backward manner. The corrected accelerometer data combined with magnetic and angular rate data can then be used to calculate the direction and magnitude of displacement that occurs during each step. This allows accurate measurement of position relative to an initial starting point.

This paper describes a self-contained method for relative position tracking of a human engaged in various types of motion involving discrete steps. This method is based on the use of a single inertial/magnetic sensor module attached to the foot. The primary contributions of this work are:

- A method for tracking 2-D and 3-D position of human movement using a self-contained inertial/magnetic sensor module.
- Preliminary experimental results for various human motion including straight line walking, circular walking, side stepping, backward walking, running, and climbing stairs.

The remainder of this paper describes in detail how accelerometer data in conjunction with orientation estimates

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produced using data from inertial/magnetic sensor modules can be used to track human position in three dimensions without any supporting infrastructure. Section II presents related work and describes the foundation on which the work presented here is built. Section III is a detailed description on the sourceless position tracking method. Experimental results are presented in Section IV. The final section is a summary and conclusions.

## II. BACKGROUND

Much research has focused on using inertial and in a few cases magnetic sensors to measure distance walked and/or track position. Many methods have involved attempts to count steps and estimate distance based on an approximate step length. Other work has double integrated acceleration data recorded during the gait swing phase to estimate distance. Few have attempted to determine the direction of motion. In most cases, distance estimation errors when using more complex inertial sensor combinations have been only slightly better than those obtained using commercial pedometers.

Simple pedometers focus on counting steps. Based on this step count and an average step length, a pedometer unit can estimate distance traveled. In pedometers, step count is generally estimated by measuring vertical acceleration using a single axis piezo-electric accelerometer or by monitoring a spring suspended horizontal lever that moves up and down in response to vertical accelerations of the hips. The accuracies of pedometer produced step counts vary greatly depending on the type of technology used, walking speed, and physical aspects of individuals being tracked [1]. Pedometers do not have the ability to differentiate between different types of gait such as running, shuffling, and side stepping. In [2], Crouter et al. tested and compared several electronic pedometers in estimating step counts and distance traveled with subjects walking on a treadmill. Several models were able to count steps to within ±1% of the actual value during normal uniform walking. Estimates of distance traveled were less accurate with most units estimating mean distance to within ±10% at a walking speed of 80 meters per minute. Overshoots tend to occurs at slower speeds. Undershoots tend to occur at higher speeds. In [3], Schneider et al. compared pedometer performance when subjects walked over a closed 400 meter course. Accuracy of step counts as well as distance estimates decreased in this more natural environment. Step count accuracy decreased to ± 3%. Since walking speed and stride length was no longer artificially controlled using a treadmill, the accuracy of distance estimates showed a greater decrease.

In [4], Pappas et al. describe a reliable gait phase detection system based on a single axis angular rate sensor and three force sensitive resistors. In this system, all motion is assumed to take place in the sagittal plane. The angular rate sensor is mounted to the heel with its sensing axis perpendicular to the sagittal plane and is used to measure the rotational velocity of the foot. The force sensitive resistors are taped to the bottom of the same foot. Using a heuristic based algorithm designed to detect four different gait phases (stance, heel-off, swing, and heel-strike), the system was able to detect the phases with 99% reliability. Unlike simple pedometers, the described method worked well to detect gait phases during walking over level and unleveled surfaces as well as walking up and down stairs. In addition, the system demonstrated robustness in ignoring non-gait events such as standing up and sitting down, bending, and turning in place. The system did not have the ability to estimate distance or direction traveled.

Zijlstra and Hof use a single triaxial accelerometer, measured leg length, and an algorithm based on an inverted pendulum model [5] to predict the body center of mass trajectory during walking. The method determines foot contacts by monitoring for changes in sign of the forward acceleration of the lower trunk. Unlike pedometers which use a fixed step length, mean step length and walking speed are estimated based on up and down movement of the trunk. Experimental results in [6] include data from both treadmill and level ground walking trails. In most cases, the described method identified foot contacts with nearly 100% accuracy. In treadmill experiments, maximum observed differences between predicted speed and treadmill speed were no greater than 16%. In level ground walking experiments with presumably less uniform gait, differences between predicted mean speed and calculated mean speed did not exceed 20%. This method is able to detect gait event with great accuracy. However, due to the magnitude of the distance measurement errors and the inability to estimate direction of the travel, the navigation performance of this method shows little improvement over that of a simple pedometer.

Sagawa et al. [7], Sabatini et al. [8], and Cavallo et al. [9] use a combination of accelerometers and rate sensors attached to the foot to measure gait parameters and distance traveled. The Sagawa approach uses a tri-axial accelerometer and a single axis angular rate sensor attached to the toe (an atmospheric pressure sensor is used to measure change in altitude). The Sabatini and Cavallo approach uses a bi-axial accelerometer and a single axis angular rate sensor attached to the instep.

Sagawa et al. assumes that foot roll and yaw are zero during normal walking. Sabatini and Cavallo assume all motion takes place in a sagittal plane. In both cases, a rate sensor is mounted perpendicular to the sagittal plane. Gait events such as heel-off, heel-strike, and swing are detected using angular rate data. Instead of counting steps, walking speed and stride length are estimated by double integrating acceleration data during the swing phase. For best performance, the tracked subject is required to maintain a uniform walking speed and gait. Both research efforts were able to detect gait events with high levels of confidence. In limited experimental results, Sagawa et al. reports a maximum distance estimation error of 5.3% over a 30 meter course. Reported experimental results obtained while walking over a 400 meter closed course in [9] characterize errors as being much smaller with an average measured distance of 401.2 ±4.61 meters or just over a 1% error. Though GPS heading information was used in [9] to reconstruct the path of travel, neither of the systems described is able to determine the direction of displacement or position.

A great deal of research has focused on integrating inertial dead reckoning systems with positional information provided by GPS and DGPS. In [10], Jarawimut et al. implement a pedestrian navigation system. During periods of GPS availability, compass bias and average step length are updated to make dead reckoning results more closely match GPS estimates. When GPS information is unavailable, distance traveled is calculated by multiplying the number of steps times an average step length. A compass is used to estimate the direction of travel and the system is able to provide an estimate of position as long as the tracked subject is walking in a normal manner.

Other attempts to produce a personal navigation based on the integration of inertial/magnetic sensors are documented in [11] and [12]. In [11] Judd suggests that step length can be estimated based on a linear relationship with cadence. The described system consists of a GPS receiver, a three dimensional compass, and tri-axial accelerometer. The accelerometer is used as a tilt sensor to determine the horizontal component of the magnetic field and to detect foot falls. Average step length is estimated by a Kalman filter algorithm. Distance traveled is based on the product of the number of steps and the estimated step length. Again this approach is limited to level walking in open spaces. The personal navigation module described in [12] contains a tri-axial magnetometer, a tri-axial accelerometer, a barometric pressure sensor, and a GPS receiver. Distance traveled is still based on the step length/step count product. It is claimed that unlike other similar systems, a pattern recognition algorithm is used to identify acceleration signatures related to different types of movement such as forward and backward walking, lateral walking, and running. Performance claims for a commercial version of the system give a 2D positional accuracy of better than 5% of distance traveled for "forward walking under normal conditions [13]." No accuracy figures are given for other types of motion. However, in independent use of the product, the Sendero Groups reports typical errors on the order of 15% [14].

## III. Method for Tracking Position

In theory, the output of an accelerometer can be integrated twice to obtain displacement information. However, low-cost accelerometers are susceptible to drift errors. The position estimates based on double integration can diverge in a short time period lasting only a few seconds. Drift correction is thus essential for tracking position using low-cost accelerometers. In this section, a drift correction method is first described. An application of this method to position tracking of a walking person is then detailed.

### *A. Correcting Accelerometer Drift*

The drift correction method is best illustrated with the following experiment. An accelerometer is first placed on a level table top, and then is slid along a straight line for a distance of one meter. The initial and final velocities are zero. Figure 1 shows the accelerometer measurement data, as well as estimated velocity and position for such an experiment in which an Analog Devices ADXL210E accelerometer was used. The three plots on the left side show the results of the original data, and the plots on the right side show the results of the corrected data. The correction procedure is discussed below. The velocity is obtained by integrating accelerometer measurements once, and the position is obtained by integrating the velocity. While the sensor actually moved a distance of one meter, the estimated distance obtained by double integration is 0.80m as seen in the lower-left plot. A close examination of the velocity in the middle-left plot indicates that the final estimated velocity is -0.23m/s at the end of the motion period, although the sensor stopped moving and the actual velocity was zero at this point. The error in the estimated velocity is due to drift in accelerometer measurements. Because the final velocity is known to be zero in this case,

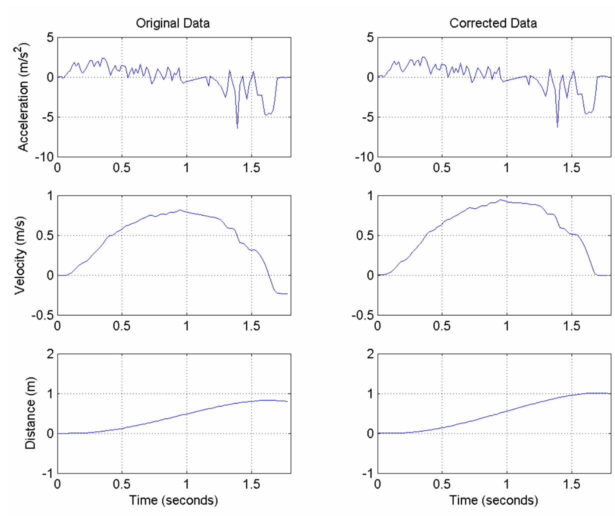


Figure 1. Results of a one-meter sliding motion experiment with original accelerometer data and integrated velocity and position on the left and the drift-corrected data and resulting velocity and position on the right side.

a drift correction can be applied to the accelerometer measurements so that the final estimated velocity is zero. The three plots on the right side of Figure 1 are the corrected acceleration, velocity, and distance. It is seen that the final velocity is now zero. As a result of this drift correction, the estimated distance moved is 1.01m. Clearly, this drift correction method makes it possible to obtain accurate position information through double integration. Many more experiments were conducted, and similar results were obtained. Figure 2 shows the results of an experiment where the sensor was moved a distance of three meters. With the uncorrected data, the final estimated distance is 2.01m, yielding an estimation error of 33%. After applying the drift correction, the final estimated distance is 2.99 m with an estimation error of only 0.3%.

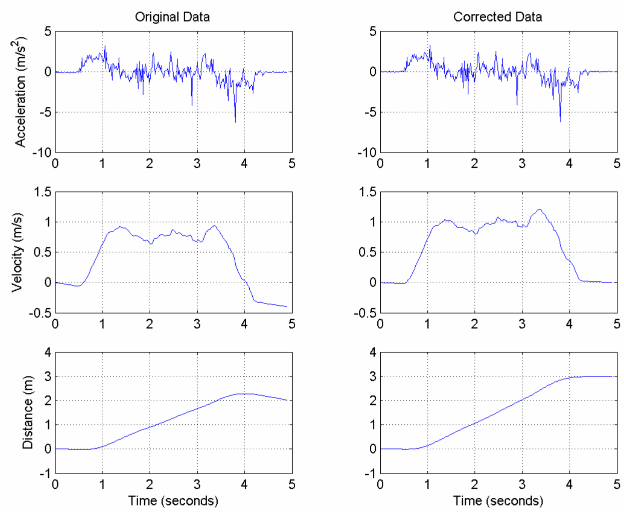


Figure 2. Original and drift-corrected data for a three-meter sliding motion experiment.

## B. *Position Tracking of a Person*

Human gait motion is cyclic in nature. During walking, each gait cycle consists of two phases: a stance phase and a swing phase. The stance phase is the portion of the cycle during which a foot is in contact with the ground. The swing phase is the portion of the cycle during which the same foot is not in contact with the ground. The stance phase takes approximately 60% of the gait cycle, and the swing phase takes the remaining 40%. During walking (rather than running or jumping), there are two periods of time in a single gait cycle when both feet are in contact with the ground. This period of double support occupies about 20% of the gait cycle [15]. Based on the results of experiments presented in the previous subsection, it is possible to obtain accurate position information by double integrating accelerometer measurements as long as drift in accelerometer measurements can be corrected. During the stance phase, the foot is in contact with the ground, and foot velocity is zero. If an inertial/magnetic sensor module is attached to a foot, drift in accelerometer measurements can be corrected each time the foot is in the stance phase of the gait cycle [7]. If the estimated foot velocity is not zero, a drift correction can be applied to the accelerometer measurements as discussed in the previous subsection. Using this approach, Sagawa, etc. [7] and Gavallo, etc. [9] reported early efforts on estimating walking distance.

In this work, an inertial/magnetic sensor module is attached to the foot, and the 3-dimensional position (not just walking distance) of a person is estimated and tracked. The inertial/magnetic sensor modules considered for this study contains triads of orthogonally mounted accelerometers, angular rate sensors, and magnetometers. Examples of such inertial/magnetic sensor modules include the MARG sensor [16], the 3DM-GX1 orientation sensor from MicroStrain [17], the nIMU from MEMSense [18], the MTx orientation tracker from Xsens [19], and the InertiaCube3 from InterSense [20]. These inertial/magnetic sensor modules are primarily designed for tracking 3-dimensional orientation. Algorithms used by these sensor modules for processing accelerometer, angular rate, and magnetometer measurements to produce orientation output typically use a Kalman filter [21]. In addition to providing orientation output in Euler angles and/or quaternions, some sensor modules including the MARG, 3DM-GX1 and nIMU also optionally provide scaled measurements of acceleration, angular rate, and magnetic field. 3DM-GX1 and nIMU are used in this study.

Acceleration measurements provided by the inertial/magnetic sensor module are in sensor or body coordinates. These measurements are first transformed into the earth coordinates. The transformation is accomplished by using the quaternion output of the sensor module. The three components of the acceleration measurements in the

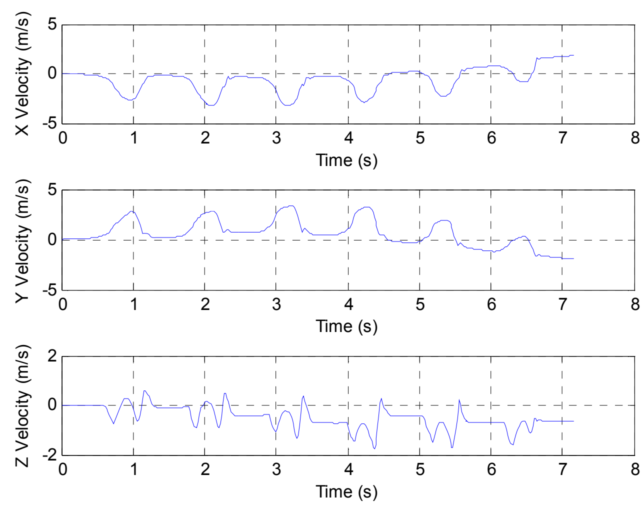


Figure 3. Three components of the velocity obtained by integrating the original acceleration measurement.

earth coordinates are then integrated to obtain velocity estimates. Figure 3 depicts the three components of the integrated velocity for an eight-meter walk. During the stance phase, each of the velocity components should be zero. However, it is seen that the estimated velocity tends to drift over the time. Applying the drift correction method discussed earlier, the corrected velocity profile is shown in Figure 4. The corrected velocity is integrated once more to obtain 3-dimensional position information. The accuracy of the position information will be discussed in the next section which examines detection of gait events during various mobility modes including straight line walking, circular walking, running, side stepping, backward walking, and climbing stairs.

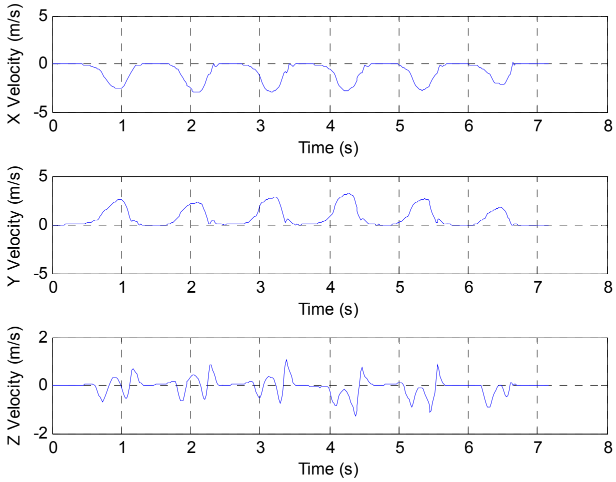


Figure 4. Velocity profile obtained from drift-corrected acceleration.

### C. Detecting Gait Events

In order to apply the drift correction method for walking as discussed above, it is necessary to reliably detect gait events, particularly the stance phase, using measurement data. Both accelerometer and angular rate data can be used for this purpose.

Figure 5 shows the three components of linear acceleration in the earth coordinates during walking. While all three acceleration components exhibit a cyclical pattern, it can be observed that z-axis acceleration data provide the strongest indication of gait events. During the stance phase, acceleration is near zero. Since there are a number of zero-crossings during the swing phase, a zero threshold and a time heuristic must be applied to the acceleration data to detect stance phases. The time heuristic is required to avoid classifying any zero crossing in the swing phase as a stance phase. If the acceleration is within the threshold for a specified period of time, the foot is determined to be in the stance phase.

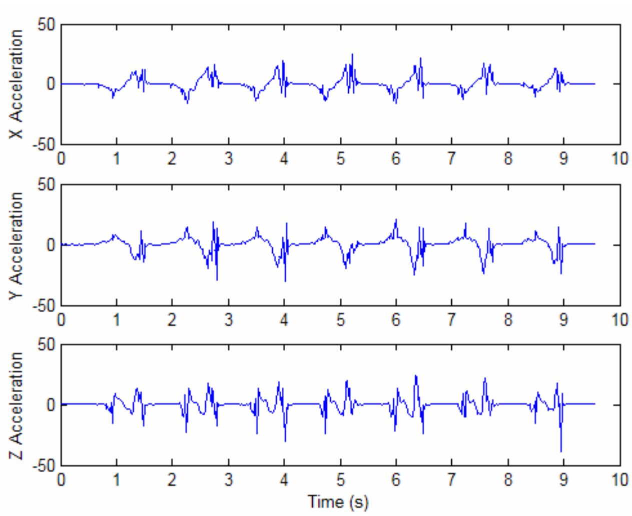


Figure 5. Three components of the foot acceleration in the earth coordinate system.

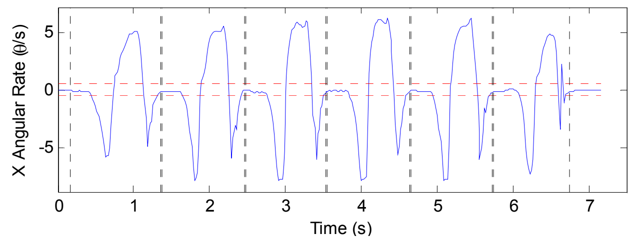


Figure 6. Foot angular rate in the ankle axis.

Angular rate measurements also provide an indication of gait events. The angular rate in the sensor coordinates measuring ankle axis rotation is more prominent in differentiating the stance phase from the swing phase. Figure 6 shows the x-axis (or ankle axis) angular rate for a typical walk. The angular rate is near zero during the stance phase. A heuristic similar to the method discussed above can be applied to the angular rate data to detect the stance phase. In empirical studies involving several different people, the use of angular rate data was found to be more reliable than acceleration data.

Figure 7. MemSense nImu mounted on foot for position tracking during walking, side stepping, and running.

## IV. Experimental Results

The following sub-sections describe preliminary experimental results demonstrating the accuracy of position estimation using inertial/magnetic sensor modules. These experiments include trials in which the tracked subject walked a specified distance in a straight line, walked around a closed circuit that was roughly circular in shape, ran a specified distance in a straight line, and finally followed a square pattern using three different types of motion. Preliminary results are also shown for walking up stairs. Data for each type of experiment was collected using several different individuals. These brief results are designed to demonstrate the robustness of position tracking using inertial/magnetic sensor modules and make apparent the wide applicability of this method to numerous applications. At the time of this writing, further experiments are under way as the position tracking method is refined.

All experiments were conducted using a single sensor module attached to the foot as depicted in Figure 7. Distances walked were measured using a standard measuring tape. Data was collected in real-time and post-processed using a program written in Matlab. Sampling rate was approximately 70 Hz.

### *A. Straight Line Walking*

Straight line walking experiments were conducted to validate the feasibility of estimating walking distance on a level surface. These experiments measure only displacement along a straight line. No attempt was made to estimate position. Table 1 shows experimental results for 24-meter straight line walk conducted in an indoor laboratory environment. Three different experimental subjects with varying stride lengths were used. The average distance estimation error for the indoor walking experiments is 5.5% with a standard deviation of 2.4%. Table 2 shows results for longer 120-meter straight line walks conducted in an outdoor environment. Two different subjects were used in these experiments. The distance estimation error for this small number of experiments was less than that observed during the indoor experiments with an average error of 1.3% and a standard deviation of 1.3%. Maximum error for the 120-meter walking experiments was 3.3%.

Table 1. Experimental results of 24-meter straight line walk.

| Experiment # | Step Count | Estimated Distance (m) | Error |
|---|---|---|---|
| 1 | 16 | 23.59 | 1.7% |
| 2 | 16 | 21.95 | 8.5% |
| 3 | 17 | 22.70 | 5.4% |
| 4 | 17 | 25.61 | 6.7% |
| 5 | 17 | 25.67 | 7.0% |
| 6 | 17 | 23.07 | 3.9% |

The marked difference in estimation accuracy between indoor and outdoor environments is attributed to errors in transforming measurement data from senor coordinates to an Earth fixed coordinate system. Magnetometer measurements along with accelerometer and angular rate measurements are used to compute an orientation quaternion, which is in turn used to transform data. In the presence of magnetic interference, orientation estimation algorithms designed for inertial/magnetic sensor modules exhibit errors in azimuth angle estimates [22]. In an indoor environment there is considerably more magnetic interference due to the presence of file cabinets, computers, monitors, and other laboratory equipment. This interference can cause estimated path of travel to appear to curve or wobble to the right and left when the true path of travel is a straight line. A correction method for these errors is currently under investigation.

Table 2. Experimental results of 120-meter straight line walk in an outdoor environment.

| Walker | Experiment # | Step Count | Distance (m) | % Error |
|---|---|---|---|---|
| A | 1 | 83 | 116.03 | 3.3% |
| A | 2 | 82 | 119.42 | 0.5% |
| B | 1 | 80 | 119.12 | 0.7% |
| B | 2 | 79 | 119.05 | 0.8% |

### *B. Straight Line Running*

The described position estimation method is applicable to any context involving repeated short periods during which angular rate and velocity are zero. During running, as with walking, there are brief periods of time in the gait cycle during which the foot is in contact with the ground. Although these zero velocity periods are relatively short, the same method can be used to correct drift in accelerometer measurements. Relative to walking, it is more difficult to detect the stance phase from running data due to the short duration of these periods.

Straight line running experiments were conducted over the same 120-meter course used in the outdoor walking experiments. Again these experiments tested only the ability to measure displacement along a straight line. Table 3 shows the results of two running experiments over a 120-meter long course. The maximum error for these experiments was within 4.75% of the actual distance covered.

Table 3. Experimental results of 120-meter straight line running

| Test # | Step Count | Actual Distance (m) | Estimated Distance (m) | Error |
|---|---|---|---|---|
| 1 | 57 | 1 20.0 | 115.4 | 3.80% |
| 2 | 54 | 120.0 | 114.3 | 4.75% |

### *C. Circular Walking*

Circular or curved walking experiments were the first to be conducted in order to validate the feasibility of tracking 2-D position. During these experiments the position of the foot was simultaneously monitored by an optical tracking system.

Figure 8 shows the position as estimated using inertial/magnetic sensor module data. Both axes are plotted in meters. The starting and ending point for the foot was the same point. This point is (0, 0) in the plot. Although truth reference data is not available as of the time of this writing, the accuracy of 2-D position tracking can be seen by observing that the estimated trajectory returns to the starting point following the period during which the walk occurred with high accuracy.

### *D. Combined Forward Walking, Side Stepping, and Backward Walking*

To demonstrate that the position tracking method can be applied to mixed types of human movement, a 5.5 meter square pattern was measured and marked in an outdoor environment. The test subject followed this marked course by walking forward on the first leg of the square from (0,0) position to about (-4,3) position, side stepping to the right on the second leg of the square, walking backward on the third leg of the square, and side stepping to the left on the last leg of the square before the foot was returned to the starting point. Figure 9 shows the position tracking results for this mixed motion experiment. The x-axis is the north direction, and the y-axis is in the east direction. The starting and ending point is again (0, 0). It can be observed that the end point and starting point almost coincide, with a separating distance of 0.08 meters. The estimated total walking distance is 21.6 meters, while the actual total distance is 22.0 meters giving a distance estimation error of 1.8%.

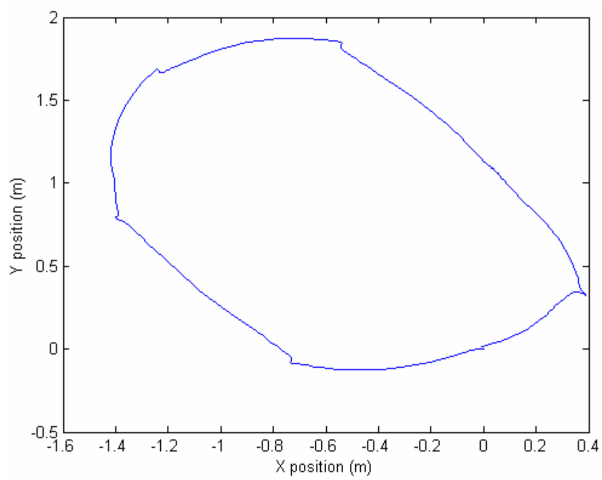


Figure 8. Position tracking of circular walking trajectory.

### *E. Climbing Stairs*

The inertial/magnetic sensor module provides 3-dimensional acceleration measurements in x-, y-, and z-axes. Thus, it is possible to track 3-dimensional position. The experiments described so far were primarily concerned with correcting and integrating x- and y-axis acceleration. Vertical axis acceleration can be corrected and integrated in the same manner in order to estimate relative height. Figure 10 depicts the 3-D estimated trajectory of a person who climbed the stairs shown in Figure 11. It can be qualitatively observed that the estimated trajectory in Figure 10 closely resembles the actual profile of stairs.

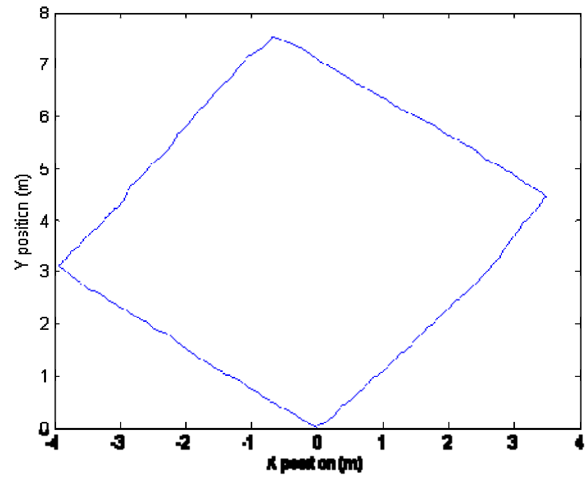


Figure 9. Position tracking results of combined forward walking, side stepping, and backward walking.

## V. Work In Progress

At the time of this writing further experiments are being conducted to evaluate, improve, and document the accuracy of position estimation using inertial/magnetic sensor modules. These experiments include mixed motion types and additional tracking methods for the purpose of providing truth data.

The experimental results provided in this paper were obtained by post-processing the sensor data. Efforts are currently underway to implement a real-time system. This system will be integrated into an immersive virtual simulation.

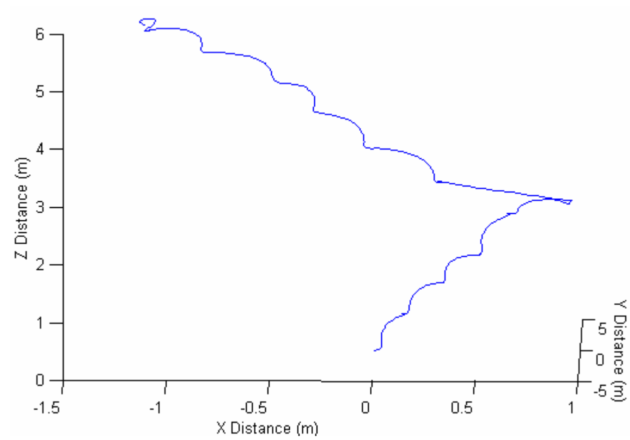


Figure 10. Estimated 3-D position of a person climbing stairs shown in the next figure.

Figure 11. Photo of the stairs used in the experiment for estimating 3-D position.

As seen in the indoor walking experiments, orientation estimation errors caused by a non-uniform magnetic environment can cause errors in transforming data from sensor coordinates to Earth coordinates. A correction method has been devised and is currently being tested.

Work is also in progress to evaluate the feasibility of the method for estimating the position of mobile robots that make a stop from time to time to provide instances of "stance phase" for correcting drift.

## VI. Conclusion

Self-contained position tracking using data from inertial/magnetic modules has applicability to a wide number of applications. Preliminary experimental results presented in this paper document that this technique can be used to track three dimensional position during a variety of motion types. Estimated errors from these experiments indicate that the method is accurate. Work is currently underway to further refine the method.

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